Drag Reduction of High Altitude Airships by Active Boundary Layer Control* (Cusp Effect)

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The aerodynamic characteristics of station-keeping airships at high Reynolds numbers were examined. The boundary layer flow developed on the hull surface was sucked in by an axial flow fan through a slot located at the rear part of the airship and the sucked-in gas was blown out as a jet. Two models, one with and one without a cusp attached to the inlet of the suction slot, were designed to validate the effects of the cusp. The flow field near the inlet, in particular the pressure on the hull surface, was measured by varying the suction flow rate. We obtained the form drag data by integrating the pressure distribution in a wide range of Reynolds numbers and of suction flow rates. Taking into account the jet thrust and the calculated friction drag, we determined the total drag and evaluated the role of the cusp. It has been found that the effects of the cusp are significant and responsible for reducing the drag.

Key Words: Transition, Jet, Boundary Layer, Pressure Distribution, Cusp, Airship

1. Introduction

The Mechanical Engineering Laboratory of the Japanese Ministry of International Trade and Industry has recently coordinated for the High-Altitude Long Range Observational Platform (HALROP) research and development program on unmanned airships. The HALROP is expected to maintain its position in the stratosphere, or station-keep, at an altitude of 20 km for an indefinite amount of time. There are abundant applications for the HALROP such as remote sensing, telecommunications, and in

situ environmental monitoring⁽¹⁾.

We developed wind tunnel models capable of active boundary layer control to optimize the aerodynamics of the HALROP. The concept of an aerodynamic shape with active boundary layer control using suction has been proposed by Goldschmied^{(2),(3)} and our design is based on his shapes. Experiments were then conducted on these models in a cryogenic wind tunnel capable of generating the desired range of Reynolds numbers located in the Institute of Engineering Mechanics at the University of Tsukuba. This paper discusses our findings on the suction effects on the boundary layer control with special emphasis on the presence of a cusp attached to the inlet of the suction slot. Pressure distributions were measured on the model surfaces and the associated effects on form drag on the hull were examined. Furthermore, we calculated velocity distributions on the hull surface based on the inviscid theory and then numerically estimated the friction drag after solving the boundary layer equation together with the inviscid velocity distribution.

The experiments were conducted on three models capable of boundary layer control. They were

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designated HALROP-C94, HALROP-C95, and HALROP-C96. For the suction effect on the model's drag reduction could not be determined on HALROP-C94. This was probably due to the inappropriate location of the suction slot and the shape. These seemed to prevent the air from being sucked efficiently. The slot location was shifted upstream and a circular cusp was attached to the inlet slot on HALROP-C95. Part of the findings of the wind tunnel tests on HALROP-C95 has been published already⁽⁴⁾. HALROP-C96 has the same hull shape as HALROP-C95 except it has no cusp.

Our main purpose was to study the cusp effect on the suction efficiency and hence on the drag reduction. In order to obtain the friction drag, an inviscid flow calculation was performed and the velocities around the models were estimated. The friction drag was derived by solving the boundary layer equation with the velocity distribution on the hull surface. A method proposed by Pohlhausen⁽⁶⁾ and Head's method^{(7),(8)} were utilized for laminar boundary layer and turbulent one, respectively. The force of the thrust from the exhaust jet was estimated in addition to the form and friction drags on the model's shape. Taking into account these three forces, we examined whether or not a "zero-drag" condition, where the thrust and the drag forces are equal, could be achieved. "Zero-drag" implies a steady-state flight condition at the required velocity for station-keeping an airship.

2. Experimental Models

The only difference between HALROP-C95 and HALROP-C96 is that HALROP-C95 has a cusp in the inlet of the suction slot. Some applications of a cusp to flow control have already been reported⁽⁹⁾. However, little is known on a cusp's preventative effect on the boundary layer separation. Therefore we examined the flow around airship hulls with a cusp (HALROP-C95) and without a cusp (HALROP-C96).

Since the scaled cusp shape was too small to manufacture easily, we chose to simplify the shape by making the internal concave curve a circular arc with a 3 mm radius. The rear parts of the hulls consist of a mid-body and a tail cone shown in Figs. 1 and 2. The curve around the inlet for HALROP-C96 was engineered so that the mid-body will connect smoothly to the suction slot.

3. Experimental Procedures

The pressure distribution as well as the jet flow emerging from the rear outlet was measured in our experiments. The jet flow was measured in order to determine the suction discharge parameters. For further details of pressure measurements see Ref. (4).

Fig. 1 Profile of two models

Fig. 2 Definition of slot width (slot width=7 mm)

The width of the suction slot is important since it governs the flow field around the suction inlet. The width of the suction slot was defined as the width of the flow path of the slot and not the width of the inlet opening. Therefore the model with a cusp and the model without a cusp have different inlet widths. For example, Fig. 2 shows a 7 mm flow path with a 4 mm inlet slot. Since the inner curve of the cusp has a 3 mm radius, the flow path is 3 mm wider than without a cusp. Experiments were performed at various path widths. However, in this paper we present only 7 mm case with a cusp and the 4 mm case without a cusp.

4. Calculation Methods

Calculations were made for two purposes. The first was to determine the velocity and pressure distributions on the hull surface. The second was to determine the boundary layer development with the velocity distribution based on inviscid theory.

4.1 Inviscid calculation by vortex element method

We determined the intensity of the ring vortices by deriving the induced velocity of a vortex ring by the Bio-Savart Law, superimposing the induced velocities on the surface from all the ring vortices and setting the normal components to the surface to be zero. Inviscid pressure distributions are easy to derive from the velocity distributions and the results are indicated as "inviscid" in the following figures.

4.2 Boundary layer development

The boundary layer was calculated in order to obtain the friction drag. The velocity distribution required for the drag calculation was taken from the inviscid estimations described above. The calculation method proposed by Pohlhausen⁽⁶⁾ was used for laminar boundary layers and Head's method^{(7),(8)} was used for turbulent boundary layers. The boundary layer thickness, momentum thickness, and friction force were estimated.

5. Experimental Result

We measured suction discharges as a preliminary experiment in the first step. Then we introduced two effective parameters, suction velocity ratio r_s and suction flow coefficient CQ to distinguish the suction effects. The suction velocity ratio is defined as the ratio of suction velocity to the local inviscid velocity at the slot inlet. This ratio is useful for the evaluation of suction effects for preventing boundary layer separation, which is why it was used in the previous paper⁽⁴⁾ for the same purposes. However, this is not always useful in comparing different slot shapes as in this study, because the suction opening areas differ from each other. On the other hand, the suction flow coefficient CQ , which depends only on the flow rate, is defined by

$$CQ = \frac{Q}{U_0 V^{2/3}}, \quad (1)$$

where Q is the suction flow rate, U_0 the free stream velocity, and V the displacement volume of the airship hull. In this parameter the hull volume is taken into account because the volume efficiency is important in considering the optimization of airships and similar lighter-than-air vehicles. For the same reasons as CQ , the Reynolds number is also defined in terms of a volume variable, $V^{1/3}$, as shown in the

following equation,

$$R_v = \frac{U_0 V^{1/3}}{\nu}, \quad (2)$$

where ν is the kinematic viscosity.

5.1 Four regions of flows and cusp effects

Experiments were conducted for a wide range of Reynolds numbers with special emphasis on boundary layer control. Pressure distributions around the airship were classified into four typical regions according to their flow characteristics, which are identical to the previous paper⁽⁴⁾ and similar to the flow characteristics around a circular cylinder⁽⁹⁾. The four regions are called subcritical, critical, supercritical, and hypercritical. Pressure distributions in each region for both cases, with and without a cusp, are shown in Figs. 3 through 6. The inlet slot widths used for these figures are 4 mm with the cusp and 7 mm without the cusp. It should be noted that when the widths of inlet slot openings are the same then the internal flow path slot widths are different. We investigated the cusp effects on pressure distribution. We used the suction flow coefficient CQ but not the suction velocity ratio r_s as a measure of the suction discharge. The ratio r_s is affected by the local geometry of the suction inlet and hence is not introduced into this paper. In the figures, "inviscid" indicates the pressure distributions derived from the inviscid theory calculations.

Figure 3 shows the pressure distribution in the subcritical region, $R_v = 3.44 \times 10^5$. The boundary layer separates from the hull surface at the maximum diameter hull station which is located at $x/L = 0.575$ when $CQ = 0$. Regardless of whether there was a cusp or not, the separation took place until the Reynolds number became $R_v = 4 \times 10^5$. In both cases, with and without a cusp, increasing CQ suction hardly affects the pressure distribution and the boundary layer remains detached until $CQ = 0.015$. For the model with a cusp, the suction did have important effects on the pressure distribution in the region $CQ \geq 0.017$. At suction flow coefficients in this region, the pressure and also velocity distributions are largely affected in the aft region downstream of the maximum diameter hull station and eventually they become close to those of inviscid flows. That the pressure continues to decrease beyond the maximum diameter hull station means the flow is accelerated beyond this station. This is a favorable phenomenon with respect to delaying the separation. From around $x/L = 0.7$ up to the inlet slot the pressure coefficient remains constant; that implies large separation bubbles. After these bubbles the pressure recovers largely across the suction slot. This indicates a reattachment of the flow. For the model without a cusp, the pressure coefficient has lower value upstream of the suction slot even if

Fig. 3 Surface pressure distribution (Subcritical region, $R_v = 3.44 \times 10^5$)

suction flow rates are increased. This leads to increased drag, which will be shown later. It should be noted that for the model with a cusp the pressure coefficient in front of the suction slot increases and becomes closer to the inviscid flow as the suction discharge is increased. This is an important role of the cusp.

Figure 4 shows the pressure distributions in the critical region, $R_v = 7.25 \times 10^5$. There was no perceptible flow separation at the maximum diameter hull station. Even when there was no suction control, fluid flowed along the surface except for a small separation bubble at a station upstream of the suction slot at $x/L = 0.72$. We speculate that the downstream flow becomes turbulent after reattachment. Here we also note the pressure coefficient just ahead of the suction inlet. For the model with a cusp, the pressure coefficient upstream of the suction slot is nearly equal to zero and slightly higher than that predicted by the inviscid theory when the suction flow rate is zero. This indicates there is a tendency for the flow to separate. For the model without a cusp, the pressure coefficient is very close to the inviscid one. For the model with a cusp, however, the pressure coefficient moves closer to the inviscid flow as the suction

Fig. 4 Surface pressure distribution (Critical region, $R_v = 7.25 \times 10^5$)

coefficient increases. For the model without a cusp the velocity increases therefore the pressure decreases as the suction discharge increases.

Figure 5 shows the pressure distributions in the supercritical region, $R_v = 2.06 \times 10^6$. The separation bubbles observed at $x/L = 0.72$ in the critical region totally disappear. This is understandable from our knowledge of the flows around a circular cylinder. The flow transition takes place and the boundary layer becomes turbulent there. The pressure distributions near the suction inlet slot are quite different between the model with a cusp and the model without a cusp. On the model with a cusp, the separation occurs when the suction flow rate is quite low. This may be caused by high pressure ahead of the suction inlet slot, as in the critical region. However, stronger suction soon causes a completely attached flow. On the model without a cusp, the flow attaches to the rearmost surface of the slot. Since the pressure just upstream of the suction inlet is too low, an extra drag is generated. Higher suction flows seem to increase this phenomenon.

Figure 6 shows the pressure distributions in the hypercritical region, $R_v = 7.09 \times 10^6$. The pressure coefficients upstream are a little higher than in the

Fig. 5 Surface pressure distribution (Supercritical region, $R_v = 2.06 \times 10^6$)

Fig. 6 Surface pressure distribution (Hypercritical region, $R_v = 7.09 \times 10^6$)

other regions. It is plausible that the boundary layer becomes turbulent in the upstream regions. The turbulent boundary layer detaches in the downstream regions and hence a completely attached flow is not attained except for the model with the cusp at $CQ = 0.023$ although the flow comes closer to the inviscid flow as the suction increases. A much stronger suction is required to create a completely attached flow in this region. The motor used in these experiments was too weak to generate a completely attached flow. It is important to note that the downstream pressure distributions are similar in both models, the one with the cusp and the other without, but the pressure just before suction inlet slot is different. The model with the cusp does not augment the velocity beyond the inviscid flow velocity while the model without a cusp produces an extra velocity increase. As in the supercritical region, this leads to the increase of form drag for the model without a cusp.

5.2 Form drag variations versus Reynolds numbers

By integrating the pressure over the entire hull surface, we estimated the form drag coefficient as a function of the Reynolds number. In the estimation the pressures further downstream of the last pressure

tap⁽⁴⁾, say at station 26, were set equal to the pressure at station 26. Figure 7 shows the variations in the form drag coefficient versus the Reynolds numbers for the model with the cusp and a slot width of 7 mm. Figures 8 and 9 show the variations in the form drag coefficient versus the Reynolds numbers for the models without the cusp and slot widths of 4 mm and 7 mm, respectively. The abscissa denotes the Reynolds number in a logarithmic scale and the ordinate denotes the form drag coefficient C_D . The previously defined four regions (subcritical, critical, supercritical, and hypercritical), are also indicated at the upper part of the figure. The overall phenomena in the four regions are very similar to those of a circular cylinder⁽⁹⁾. However, the regional distinctions made in this paper would not be precise enough to be valid for all cases, because these classifications are only based on the models examined in this experiment, namely models with and without a cusp with 4 mm and 7 mm suction slot widths.

In the subcritical region the form drag coefficient is very large when the suction discharge is weak because the flow separates at the maximum hull radius. In the critical region the form drag coefficient becomes smaller because completely attached flow is

Fig. 7 Form drag coefficient (with cusp)

Fig. 8 Form drag coefficient (without cusp)

Fig. 9 Form drag coefficient (without cusp)

accomplished. The corresponding drag is small for both cases, with and without a cusp; but the value is smaller for the model with a cusp than without a cusp. The reason for this is that the pressure just upstream of the suction slot inlet is not close to the inviscid flow

for the model without a cusp. The magnitude of the drag in the subcritical region is ten times larger than the smallest pressure value in the model with a cusp. In the supercritical region the drag becomes much greater because the separation point located at the rear of the model moves substantially upstream as the Reynolds number is increased. In the hypercritical region the drag coefficient appears to be almost constant since the boundary layer separates at almost a fixed point.

When no suction is applied the difference between the two models, with and without a cusp, is very small. In general, if suction is applied then the drag coefficient for the model with the cusp is lower than the model without a cusp; especially for the critical and supercritical regions. As mentioned before, the reason for this is the pressure value just upstream of the suction inlet slot. Comparing the model without a cusp with a suction inlet slot width of 4 mm to that of the same model with a 7 mm suction inlet slot width, we find that the 4 mm slot width creates somewhat more drag, particularly in the critical region. The suction creates faster flow upstream of the suction inlet slot for the 4 mm width. The higher velocity creates lower pressure which leads to greater drag. On the other hand, this is not the case for the model with a cusp. It can be said that the cusp prevents the velocity from increasing upstream of the suction inlet slot and hence keeps the pressure constant even when the suction discharge is increased.

5.3 Total drag coefficient including thrust force

So far, we have considered form drag only. The total drag is the sum of the form drag and friction drag. Due to the limitations of the experimental equipment, we could not measure the friction drag separately. For this reason we calculated a numerical estimation of the friction drag. In addition to the friction drag calculations, we evaluated the thrust force emerging from the rear jet. We defined a “zero-drag” condition as a state where the sum of the total drag and the thrust force equals zero. The “zero-drag” concept is important to station-keeping an airship in the stratosphere. If the drag and thrust cannot be balanced, the airship will move off station.

The total drag C_{total} is expressed as

$$C_{total} = C_D + C_f, \quad (3)$$

where all the coefficients are non-dimensionalized in terms of $V^{2/3}$ as a characteristic area. In the friction drag estimation, it is assumed that the magnitude of the suction does not affect the drag. Strictly speaking, this assumption is incorrect; but it does not produce any serious problems in judging whether the “zero-drag” condition can be achieved or not.

The thrust T_j produced by the rear jet propulsion

is expressed as

$$T_j = \rho Q u_j, \quad (4)$$

where Q is the jet flow rate and u_j the jet flow velocity. This is normalized in a manner similar to drag coefficients as

$$C_j = \frac{\rho Q u_j}{\frac{1}{2} \rho U_0^2 V^{2/3}}. \quad (5)$$

The overall drag coefficient is calculated from $C_{total} - C_j$. Figures 10 - 12 show the variations of the overall drag coefficients as a function of CQ for several Reynolds number values. Figure 10 shows the data for the model with a cusp and a suction inlet slot width of 7 mm. It is clear from the data shown in this figure that a $CQ = 0.0275$ in the subcritical region is required to achieve a "zero-drag" condition. The CQ value required to achieve a "zero-drag" condition in the critical region is low. The minimum values for CQ are obtained at Reynolds numbers 1.10×10^6 and

Fig. 10 Drag coefficient (with cusp, slot width=7 mm)

Fig. 11 Drag coefficient (without cusp, slot width=4 mm)

2.06×10^6 , which are high Reynolds numbers in this region. The value of CQ corresponding to these Reynolds numbers is 0.017. The drag characteristics in the supercritical region have not been well observed. The drag increases again in the hypercritical region because separations occur at the rear of the suction inlet slot. We could not determine the "zero-drag" condition in this region because the motor was not powerful enough to prevent boundary layer separations.

Figures 11 and 12 show the data for the model without a cusp and 4 mm and 7 mm suction inlet slots, respectively. The symbols are the same as those used in Fig. 10. In comparison to the model with the cusp, the "zero-drag" condition can only be attained in a limited part of the critical and supercritical regions since the form drag is high there. The "zero-drag" condition was only attained for the 7 mm slot width in the subcritical region. The CQ value was estimated as 0.028. The CQ value for the "zero-drag" condition becomes smaller beyond the critical Reynolds number. It was estimated as 0.023 irrespective of the suction inlet slot width and is large compared to the model with a cusp.

6. Summary

We conducted experiments on two types of air-ship models, one with and one without a cusp. Form drags were estimated from the pressure distributions and friction drags were derived by integrating the boundary layer equation. In addition, the thrust forces emerging from the rear jet were also considered. As a result of our observations, calculations and analysis we conclude the following:

(1) Based on the characteristics of the pressure distributions on the hull surface, flows around the

Fig. 12 Drag coefficient (without cusp, slot width=7 mm)

airship can be roughly divided into four regions defined by varying Reynolds number values. They are:

1. Subcritical region, $R_v < 4 \times 10^5$;
2. Critical region, $R = 4 \times 10^5 - 2 \times 10^6$;
3. Supercritical region, $R_v = 2 \times 10^6 - 4 \times 10^6$;
4. Hypercritical region, $R_v > 4 \times 10^6$.

The four roughly divided regions shown above are for all of the models regardless of whether they have a cusp or not.

(2) In active boundary layer separation control, the cusp prevents the increase of velocity associated with the suction flow rates upstream of the suction inlet slot. The cusp plays an important role in reducing the form drag, which is considerable in the critical and supercritical regions.

(3) Achieving completely attached flow or the flow with the minimum form drag depends upon presence or absence of the cusp and the width of the suction inlet slot. The minimum value of the suction flow rate is achieved in the critical region.

(4) The "zero-drag" condition can be obtained by taking the form drag, friction drag and thrust force into consideration. The minimum CQ values for the "zero-drag" conditions are $CQ=0.017$ for the model with a cusp and $CQ=0.023$ for the model without a cusp.

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